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Impacts of Coordinating the Colors of Flashing Warning Lights and Vehicle Markings on Driver Perception

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Abstract

Flashing lights on emergency and maintenance vehicles should be critical components to alerting, informing and managing drivers as they navigate around work zones, vehicle accidents and other roadway emergency incident scenes. These vehicles often also use distinctive colors and markings to identify the type of vehicle and potentially provide drivers with information about the nature of the incident they are approaching. In order to begin to understand how these elements (flashing lights and vehicle/marking colors) contribute to perception, a study was carried out in which participants viewed pairs of roadway scenes using scale model vehicles and lights adjusted to produce similar apparent intensities as full-scale lighting systems. In some cases the colors of the flashing lights were coordinated with those of the vehicle and its reflective markings, and in other cases the colors were not coordinated. Participants reported which scenes appeared to be fire emergencies, as opposed to a non-emergency situation such as a roadway work zone. In addition to differences between different amounts of coordination between the color of the lights and the vehicles and markings, there were individual differences among the participants. The results can guide future research and can help in developing guidelines for the use of flashing light and vehicle marking colors to reinforce driver perception and awareness.

Introduction

First responders and front-line service workers engaged in road maintenance and repair operations are at higher risk than many other workers for being injured or killed at work [1,2]. Because of this increased risk, the vehicles used by these workers are outfitted with specialized colors, markings and flashing lights to help make them more conspicuous and distinct from other vehicles, hopefully providing approaching drivers with added information about how they should safely approach and pass vehicles in different situations. Because the color red is often associated with increased danger or emergency [3], fire trucks are commonly painted red and often use flashing red lights, whereas maintenance vehicles like those used in work zones most commonly use flashing yellow lights.

Despite some research suggesting that lighter colors for fire apparatus could help make these vehicles more visible to nearby drivers [4], a review by the Federal Emergency Management Agency [5] suggested that the familiarity of an emergency vehicle's color was a more important factor in helping drivers identify the type of vehicle. Since flashing lights and retroreflective markings on these vehicles help increase their conspicuity, and because some studies have not shown a safety benefit from lighter fire truck colors, at least 85% of fire engines in the U.S. are red [6].

As a preliminary step in understanding what visual cues people might use to identify whether a vehicle with flashing lights might be involved in a situation such as a fire emergency or a road construction site, and which factors (e.g., color of vehicle marking versus flashing light color), a pilot experiment was carried out. This experiment utilized a forced-choice protocol whereby participants were required to identify one of two groups of vehicles in the field of view as a specific incident type. For example, one might expect people to be more likely to identify red vehicles with red flashing lights as part of a "fire emergency" scene, than yellow vehicles with yellow flashing lights. To evaluate whether the vehicle color or the flashing light color is a more important factor in making such an identification, a group of red vehicles with yellow lights could be compared to yellow vehicles with red lights, and participants asked to identify which of the two alternatives represents a fire emergency.

In such a protocol, some subjects might be more likely to base their identification upon the vehicle color and others upon the flashing light color. Others might not consistently base their identification upon the same factor. And some individuals might base their identification upon other factors such as the left-right position of the groups of vehicles [7]. In carrying out such an evaluation, then, it is important to "calibrate" each participant in terms of the visual factors they rely

upon to identify the type of incident they are viewing, and whether they exhibit positional or other biases unrelated to vehicle and flashing light colors. A long-term objective of this research will be to identify configurations of vehicle colors and flashing lights that maximize the likelihood of vehicles along the road being identified similarly by as many individuals as possible. The pilot experiment described here is an initial step toward that objective.

Method

An O-scale (48:1) scene of a six-lane highway (Figure 1) was created in the photometric laboratory of the Light and Health Research Center in Albany, NY. Pairs of red and/or yellow vehicles were positioned along the left or right side of the road. At the top of each vehicle was a pair of red/yellow dual-color LEDs adjusted so that each LED could produce a vertical illuminance of 0.2 lux at the eyes of an observer located approximately 7 ft (2.1 m) from the vehicles. The LEDs were configured to produce three 100-ms pulses of light, separated by 100 ms, which could be repeated. The pair of lights on each vehicle flashed in unison, but the timing for each vehicle was adjusted by small amounts so that the lights on each vehicle went in and out of phase with each other, mimicking the behavior commonly seen on multiple vehicles with flashing lights. When the LEDs were not producing 0.2 lux at the observer's eye position (simulating the appearance of a light viewed from 100 m that had a luminous intensity of 2000 cd), they produced an intensity one-tenth that value. This was done to produce "high-low" rather than "on-off" flashing found in prior research to enhance visual closure detection [8].

In the initial experimental sessions (Experiment 1), the color of the flashing lights (red or yellow) always matched the color of the vehicle. In addition, the luminous intensities were matched between red and yellow flashing lights, and the sequence of three pulses was repeated with a frequency of 1 Hz. In each trial subjects seated at the far end of the scale model would look down at a laptop computer with instructions to look up when notified by the experimenter, and then to identify which pair of vehicles (left or right) represented a "fire emergency" (a more "urgent" situation than a "work zone," for example) by pressing either the left or right arrow key on the keyboard. After each response the subject would return their gaze to the laptop computer and the experimenter would set up the next condition. Overall there were sixteen different pairs of scenes and each pair was viewed three times.

In Experiment 2, the same procedure was used, except that the color of the flashing lights always differed from the color of the vehicle and its markings. Finally, Experiment 3 also used the same procedure as the first. The colors of each vehicle and its flashing lights always matched, but the intensity of the red flashing lights was increased by 50% and the intensity of the yellow flashing lights decreased by 50%. In addition, for the third experiment, the frequency for the sequence of pulses for the red flashing lights was increased to 2 Hz. As a result, the red lights flashed faster and brighter than the yellow lights.

In all experiments, room lights were switched on so that the horizontal illuminance was 500 lux on the road where the scale model vehicles were located. The same ten subjects (7 male/3 female, mean age 51 years, s.d. 14) participated in all three experiments. All ten individuals were licensed drivers.

The study was reviewed and determined to be exempt human subjects research by the Institutional Review Board (IRB) at the Icahn School of Medicine at Mount Sinai.

Results

Experiment 1

Although it was expected based on previous literature (e.g., [3]) that the color red would be more likely to be associated with an emergency situation, it was also anticipated that each subject might have his or her own criteria for identifying which pair of vehicles they would identify as a fire emergency (e.g., vehicle color versus flashing light color). Further, it was possible that some subjects might have an inherent positional bias (e.g., left or right) in terms of which pair of vehicles they might identify as a fire emergency. In order to test whether these expectations were met, the pairs of conditions were divided into several categories:

- Those in which the pair of vehicles on the left side were identical to the pair on the right side
- Those in which two red vehicles were on one side, and two yellow vehicles were on the other
- Those in which two red vehicles were on one side, and a red and a yellow vehicle were on the other (this is what is illustrated in Figure 1)
- Those in which two yellow vehicles were on one side, and a red and a yellow vehicle were on the other

To assess whether there was a statistically significant bias in terms of which pair of vehicles was identified as a fire emergency for a given category of comparison, Chi-square tests were used with a criterion of $p<0.05$ for rejecting the null hypothesis that there was no difference in which pair of

FIGURE 1 Photograph of scale-model roadway scene with two pairs of vehicles (two red vehicles on the left, and a red and a yellow vehicle on the right).

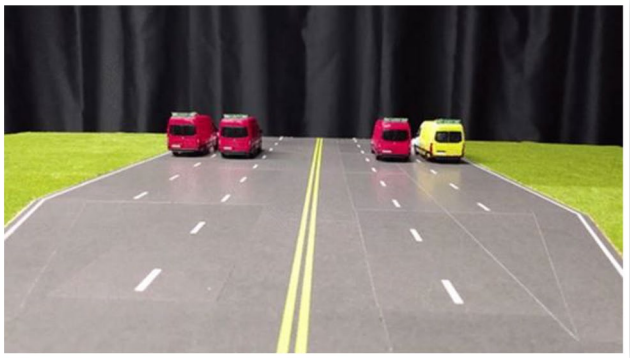
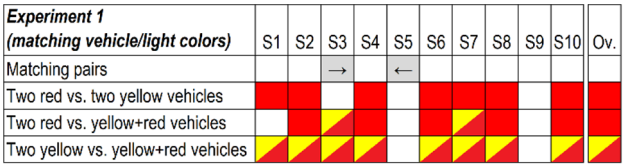


TABLE 1 Summary of statistical comparisons for each category of judgment in Experiment 1, for each individual subject (S1-S10) and for all subjects overall. In the "Matching pairs" row, shaded cells correspond to a statistically significant ($p<0.05$) left/right bias (denoted by the direction of the arrow in the cell). In the other rows, the colors of shaded cells correspond to the vehicle pair that was chosen most frequently, when there was a statistically significant ($p<0.05$) preference for a choice. Red cells denote a pair of red vehicles; split yellow/red cells denote a yellow with a red vehicle. Unshaded cells in all rows indicate that the preference was not statistically significantly different from chance (50%).



vehicles was identified as a fire emergency. Table 1 summarizes the statistical analyses for each individual subject and for the overall experiment.

Beginning with the overall experimental results in the rightmost column of Table 1, it can be seen that there was no statistically significant overall left-right bias among all of the comparisons when the pairs of vehicles matched each other. In addition, the overall results reveal a statistically significant ($p<0.05$) identification of two red vehicles (with red flashing lights) as a fire emergency when compared either to two yellow vehicles, or to a red and a yellow vehicle. The overall results also reveal a statistically significant ($p<0.05$) identification of a red and a yellow vehicle as a fire emergency when compared to two yellow vehicles.

The individual statistical comparisons in Table 1 often, but not always, are consistent with the overall results. For example, while most subjects did not exhibit a statistically significant left-right bias, two did (one favoring the pair of vehicles on the left side and one favoring the right side of the road). In addition, two subjects exhibited no preference for which pair of vehicles they identified as a fire emergency when the pairs did not match. Two additional subjects failed to exhibit a statistical preference for one of the comparison categories. Finally, two subjects chose a red with a yellow vehicle as more likely to be a fire emergency than two red vehicles, while five subjects chose the pair of red vehicles as the fire emergency when making the same comparison.

Experiment 2

In all of the conditions in Experiment 1, the colors of the flashing lights on each vehicle matched the colors of the vehicles they were on. Thus, the results of that experiment do not provide insight as to whether the color of the vehicle and its markings or the color of its flashing lights might have been more important to a particular subject when identifying a fire emergency. In order to gain insight about this question, Experiment 2 was carried out. In this experiment, the colors of the flashing lights always differed from the color of the vehicle on which they were mounted (i.e., a red vehicle always had yellow flashing lights, and a yellow vehicle always had red lights).

TABLE 2 Summary of statistical comparisons for each category of judgment in Experiment 2, for each individual subject (S1-S10) and for all subjects overall. In the "Matching pairs" row, shaded cells correspond to a statistically significant ($p<0.05$) left/right bias (denoted by the direction of the arrow in the cell). In the other rows, the colors of shaded cells correspond to the vehicle pair (based on the color of the vehicle, not on the flashing light color) that was chosen most frequently, when there was a statistically significant ($p<0.05$) preference for a choice. Red cells denote a pair of red vehicles; yellow cells denote a pair of yellow vehicles; split yellow/red cells denote a yellow with a red vehicle. Unshaded cells in all rows indicate that the preference was not statistically significantly different from chance (50%).

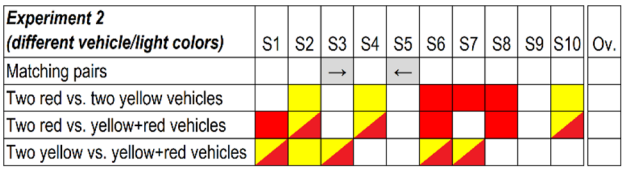


Table 2 summarizes the results of the overall and individual subjects' preferences for each comparison category. Overall, there is no statistically significant left-right bias, nor were there any statistically significant preferences for any pair of vehicles. However, individual preferences were found. For example, three subjects exhibited a statistically significant ($p<0.05$) preference to identify a pair of red vehicles (with flashing yellow lights) as a fire emergency over a pair of yellow vehicles (with flashing red lights), but three subjects exhibited the opposite preference, and four exhibited no statistically significant preference at all. In general, there was relatively little consensus among all ten subjects regarding which pairs of vehicles were identified as a fire emergency.

Experiment 3

The results from Experiments 1 and 2 revealed differences among individuals in terms of how they perceived different pairs of vehicles and in which features (e.g., vehicle colors or flashing light colors) carried more weight in making judgments about whether a particular scene represented an emergency situation. Therefore, Experiment 3 was carried out to assess the impacts of "reinforcing" perceptions of an emergency situation using additional factors, including the relative intensity and flash frequency of flashing lights. Increasing the intensity of a warning signal relative to other sources of light in the visual environment increases its perceived priority as a warning [9]. In addition, faster flashing of lights is generally judged by people as increasing the urgency of those lights [10,11].

In Experiment 3, the colors of the flashing lights (red or yellow) always matched the colors of the vehicles on which they were mounted. In addition, the intensity of the flashing red lights was increased by 50% and that of the flashing yellow lights was decreased by 50%. Further, the flash frequency of the red lights was increased so that each train of three pulses

TABLE 3 Summary of statistical comparisons for each category of judgment in Experiment 3, for each individual subject (S1-S10) and for all subjects overall. Cells in the "Matching pairs" row indicate whether there was a statistically significant left/right bias. In the other rows, the colors of shaded cells correspond to the vehicle pair (based on the color of the vehicle, not on the flashing light color) that was chosen most frequently, when there was a statistically significant ($p<0.05$) preference for a choice. Red cells denote a pair of red vehicles; split yellow/red cells denote a yellow with a red vehicle. Unshaded cells in all rows indicate that the preference was not statistically significantly different from chance (50%).

Experiment 3 (reinforced vehicle/light colors)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Ov.
Matching pairs											
Two red vs. two yellow vehicles											
Two red vs. yellow+red vehicles											
Two yellow vs. yellow+red vehicles											

of light was repeated at a frequency of 2 Hz rather than 1 Hz. It was expected that these modifications would increase the perception of red vehicles with brighter and faster red flashing lights as being part of an emergency situation.

Table 3 summarizes the results of the overall and individual subjects' responses in Experiment 3. The overall results in this experiment are identical to the overall results of Experiment 1; they show no left-right bias and a statistically significant ($p<0.05$) preference for identifying the pair of red vehicles (when compared with a pair of yellow vehicles, or with a red and a yellow vehicle) as a fire emergency. They also show that a pair consisting of a red and a yellow vehicle was more likely to be identified as a fire emergency than a pair of yellow vehicles.

Despite the similarities between the overall results from Experiments 1 and 3, there are also differences when the results at the individual subject level are examined. None of the ten subjects exhibited any left-right bias, and there appears to be a greater degree of consistency among individual subjects' responses in Experiment 3 than in Experiment 1. Nine of ten subjects exhibited a preference to identify a pair of red vehicles (with brighter, faster flashing red lights) as a fire emergency over a pair of yellow vehicles (with less bright, slower flashing yellow lights). The same proportion of subjects identified a pair of red vehicles as more likely to represent a fire emergency than a pair consisting of a red and a yellow vehicle. And all ten subjects exhibited a preference for identifying a pair consisting of a red and a yellow vehicle as a fire emergency over a pair of yellow vehicles.

Discussion and Preliminary Conclusions

The results of these preliminary experiments demonstrate that there can be substantial differences in the ways that roadside incidents containing vehicles and their flashing lights are perceived. The scale model laboratory experiments described in this paper can be a useful technique for understanding these differences. The forced-choice technique itself can identify biases such as the left-right position bias that two of the subjects in this study (S3 and S5) exhibited. One of these subjects (S3) failed to show a statistically significant preference for which pair of vehicles was identified as a fire emergency in some of the comparisons in all three experiments, and it is possible that this subject's inherent position bias influenced this result. On the other hand, the other subject exhibiting a position bias (S5) showed statistically significant preferences (which importantly were consistent with the responses of most other subjects) regarding which pairs of vehicles were identified as fire emergencies for all non-matching comparison categories in Experiment 3.

This latter result suggests that the reinforcing enhancements to the flashing red lights in Experiment 3 (i.e., increasing the relative brightness of the red lights and increasing the flash frequency of the red lights) helped this subject to make similar judgments as most of the other subjects in this experiment. Indeed, comparing Tables 1 and 3 it seems clear that the brightness and flash frequency modifications to the red lights increased the consistency of judgments among all of the subjects as to which pairs of vehicles were identified as fire emergencies.

Assuming that the color red is correctly associated with emergency situations such as a fire emergency (rather than, for example, a work zone) as suggested by previous literature [3] and by the results in Table 1 showing a greater likelihood of selecting red vehicles (with red lights) over yellow as being associated with a fire emergency, this has practical importance because Table 2 shows that some subjects seem to base their judgment about which pair of vehicles represents a fire emergency upon the red color of the vehicles, while others seem to base their judgments on the red color of the flashing lights. By adding cues based upon intensity [9] and upon the flash frequency [10,11] to flashing lights that are coordinated with the colors of vehicles and their markings, it was possible to obtain greater overall agreement (and correctness) among the subjects in this study about which pairs of vehicles were identified as fire emergencies.

Future research in this area will be carried out to characterize a larger group of subjects sampled from the general population so that the proportions of individuals who exhibit position bias or other differences from others in their judgments can be estimated, and possible countermeasures to help form more consistent judgments can be identified. In addition, it will be important to eventually undertake full-scale studies of drivers in real-world conditions to understand how drivers respond to what they perceive as emergency situations compared to other roadside scenarios.

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